

LEARNING MADE EASY

Keysight Technologies Special Edition

5G & Beyond

for
dummies[®]
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Understand the
vision for 5G

Overcome 5G's
challenges

Uncover opportunities
with 5G

Brought to
you by



Larry Miller
Jessy Cavazos

About Keysight Technologies

Keysight delivers advanced design and validation solutions that help accelerate innovation to connect and secure the world. Keysight's dedication to speed and precision extends to software-driven insights and analytics that bring tomorrow's technology products to market faster across the development lifecycle, in design simulation, prototype validation, automated software testing, manufacturing analysis, and network performance optimization and visibility in enterprise, service provider, and cloud environments. Our customers span the worldwide communications and industrial ecosystems, aerospace and defense, automotive, energy, semiconductor, and general electronics markets.

For more information about Keysight Technologies (NYSE: KEYS), visit us at www.keysight.com.



5G & Beyond

Keysight Technologies Special Edition

by Larry Miller and Jessy Cavazos

**for
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Introduction

The promise of 5G is faster and more reliable communications. 5G enables the Internet of Things (IoT), autonomous vehicles, wireless broadband, interruption-free video, and the fourth industrial revolution. When you develop 5G technology, understanding design and testing concepts and solutions across multiple dimensions is imperative.

In this book, you find out about 5G technologies and their associated challenges. You also discover solutions available to address these challenges and ways you can create new opportunities for your organization.

About This Book

5G & Beyond For Dummies, Keysight Technologies Special Edition, describes how 5G technologies are evolving. This book is conveniently organized into six chapters that

- » Explain the vision of 5G New Radio (NR) and the path to the 5G vision (Chapter 1)
- » Describe 5G device and base station development (Chapter 2)
- » Delve into Open Radio Access Network (O-RAN) challenges and solutions (Chapter 3)
- » Detail virtualization, cloudification, multi-access edge computing (MEC), observability, and security trends in 5G (Chapter 4)
- » Explore 5G opportunities and the vision for 6G (Chapter 5)
- » List the key steps to 5G deployment success (Chapter 6)

You can also refer to the glossary at the end of the book — just in case you start feeling overwhelmed by any acronyms or technical terms used in this book.

Foolish Assumptions

This book uses mainly one assumption about you: You're an engineer of some sort within the mobile ecosystem. Perhaps you work

for a chipset manufacturer, device maker, network equipment manufacturer, or network operator involved in the research, development, and manufacturing of 5G devices (such as chipsets, devices, base stations, or components) or the deployment of 5G networks. You probably know a little something about wireless communications, but you may not necessarily know about the latest 5G technologies. As such, this book is primarily for technical readers.

If that describes you, you're in the right place. If it doesn't, keep reading anyway. It's a great book, and you'll find out a few things about 5G.

Icons Used in This Book

This book occasionally uses icons to call attention to important information. Here's what you can expect:



REMEMBER

This icon points out information or a concept that may well be worth committing to your nonvolatile memory, your gray matter, or your noggin!



TECHNICAL
STUFF

If you seek to attain the seventh level of nerd-vana, perk up! This icon explains the jargon beneath the jargon and is the stuff legends — well, nerds — are made of.



TIP

Tips are appreciated, but never expected — so keep these useful nuggets of information nearby.



WARNING

These alerts point out the stuff your mother warned you about (well, probably not). But they do offer practical advice to help you avoid potentially costly mistakes.

Beyond the Book

There's only so much this short book covers, so if you find yourself wondering, "Where can I find out more?," just go to www.keysight.com/find/5g.

- » Tuning in to 5G New Radio (NR)
- » Plotting the path to 5G

Chapter 1

Realizing the Vision of 5G

The high-bandwidth and real-time capabilities of 5G hold enormous potential for society by enabling many new and unexpected use cases. In this chapter, you find out about the 5G vision, discover more about use cases, read about standards enhancements, and delve deeper into the migration path to 5G.

Looking at 5G New Radio (NR)

5G embodies the breadth and depth of innovative and comprehensive mobile wireless communications technology. The potential of 5G goes well beyond that of its predecessors. Some of the new applications it will enable are

- » Multi-gigabit wireless mobile broadband
- » Fixed broadband wireless access
- » Augmented reality (AR) and virtual reality (VR)
- » Autonomous vehicles
- » Vehicle-to-everything (V2X) communications
- » The mobile Internet of Things (IoT)
- » The wireless industrial IoT (IIoT)



REMEMBER

NR is to 5G what Long Term Evolution (LTE) is to 4G. The 5G NR standard continues to evolve to enable faster data rates, improved coverage, lower latency, higher reliability, and greater network flexibility.

The following sections break down the ins and outs of 5G to help you better understand the importance of the technology from a technical standpoint.

Vision

The vision for the 5G future is bold: It's much more than just the next iteration of mobile networks. Technological trends including cloud computing, artificial intelligence (AI) and machine learning (ML), AR and VR, and billions of connected devices are pushing the boundaries of the wireless communications system like never before.



REMEMBER

5G technology promises faster, more reliable, and near-instant connections that will universally connect people and things. 5G allows everyone to experience live events and video games in real time, make phone and video calls that feel close and intimate, and pair smart devices with AI to create a customized and personalized environment for everyone.

Use cases

The three use cases defined in 5G NR are as follows:

- » **Enhanced mobile broadband (eMBB):** eMBB refers to the target 5G peak and average data rates, capacity, and coverage as compared to conventional mobile broadband. eMBB specifies a 5G design capable of supporting up to 20 gigabits per second (Gbps) in the downlink (DL) and 10 Gbps in the uplink (UL).
- » **Massive machine-type communications (mMTC):** mMTC supports 5G IoT use cases with billions of connected devices and sensors. The use case covers both low-data-rate/low-bandwidth devices with infrequent bursts of data requiring long battery life as well as very-high-bandwidth/data-rate devices.
- » **Ultra-reliable and low-latency communications (URLLC):** URLLC focuses on applications that require fail-safe,

real-time communications. Examples include autonomous vehicles, the industrial Internet, smart grids, infrastructure protection, and intelligent transportation systems.

3GPP 5G releases

The 3rd Generation Partnership Project (3GPP) is an industry consortium responsible for developing standards for mobile telecommunications (protocols, architectures, system requirements, and so on). Release 15 (Rel-15) of the 5G NR specification is the first implementable standard for 5G, and it establishes a flexible foundation to accommodate future releases of 5G features.

Rel-15 focuses on the high-speed data rates and capacity demands of eMBB. It specifies a new air interface to enable higher data throughput and lays the groundwork for low latency and higher reliability applications. The use of millimeter-wave (mmWave) spectrum up to 52.6 gigahertz (GHz) is the key to enabling higher data throughput. At these higher frequencies, more contiguous spectrum is available to send more data through the channel. Rel-15 specifies a maximum carrier bandwidth of up to 400 megahertz (MHz) and up to 16 component carriers (CCs), and allows multiple carriers to be combined to create up to 800 MHz of channel bandwidth. Flexibility and scalability in the slot structure help support the many new and diverse use cases expected from 5G.

Figure 1-1 reviews some of the key technologies and benefits in 5G NR Rel-15 that are discussed in the following sections.

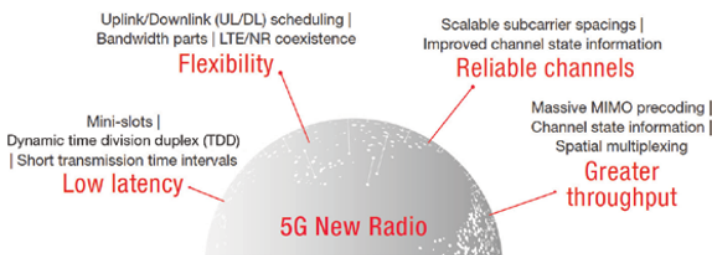


FIGURE 1-1: 5G NR Rel-15 technologies and their benefits.

Low latency

The URLLC use case is partially achieved through a concept called *mini-slots*. In LTE, transmissions adhere to the standard slot boundaries, but they aren't optimized for minimal latency.

A standard slot has 14 orthogonal frequency-division multiplexing (OFDM) symbols. As the subcarrier spacing increases, the slot duration decreases. A mini-slot is shorter in duration than a standard slot and can be located anywhere within the slot. A mini-slot is two, four, or seven OFDM symbols long. Mini-slots provide low latency payloads with an immediate start time, without needing to wait for the start of a slot boundary.

Flexibility

The maximum carrier bandwidth in LTE is 20 MHz, which when aggregated across the maximum number of carriers that the standard allows — five — creates a wider effective communication channel bandwidth of up to 100 MHz. In 5G NR, the maximum carrier bandwidth is up to 100 MHz in FR1 (up to 7.125 GHz), or up to 400 MHz in FR2 (24.25 to 52.6 GHz). The standard allows for the aggregation of multiple carriers for up to 800 MHz of channel bandwidth.



TECHNICAL
STUFF

A new innovation in 5G NR is *bandwidth parts*, where the carrier is subdivided for different purposes. Each bandwidth part has its own numerology and is signaled independently. One carrier can have mixed numerologies to support services in unlicensed bands and different levels of services — like power saving or multiplexing of numerologies.

Reliable channels

5G NR uses the cyclic prefix OFDM (CP-OFDM) waveform format. Unlike LTE, this format can be used in both the DL and the UL. Having the same waveform in both the UL and the DL enables easier implementation of things like device-to-device communication in future releases. Discrete Fourier transform spread OFDM (DFT-s-OFDM) is an optional waveform in the UL. DFT-s-OFDM reduces the demand on user equipment (UE) transmission amplifiers, helping to extend battery life.

Unlike 4G, NR allows for scalable OFDM numerology where the subcarrier spacings are no longer fixed to 15 kilohertz (kHz). Subcarrier spacing is determined by the formula $2^n \times 15$ kHz where n can be as low as -1 . Lower frequency bands use 7.5, 15, 30, and 60 kHz subcarrier spacings, and higher frequency bands use 60, 120, and 240 kHz subcarrier spacings.

Scalable numerology enables scalable slot duration to optimize throughput, latency, or reliability for different service levels. Larger subcarrier spacing at higher frequencies also helps with the robustness of the waveform because integrated phase noise is a greater issue in mmWave designs (see Figure 1-2).

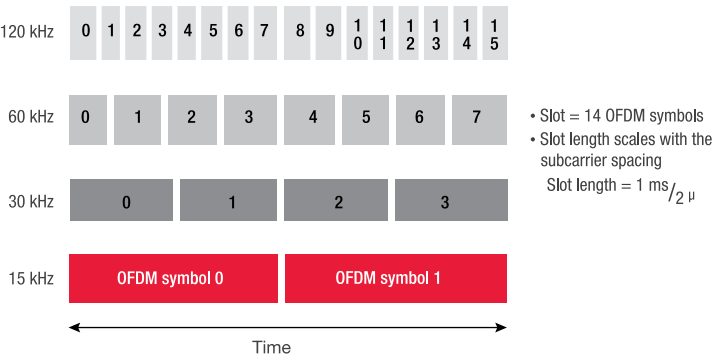


FIGURE 1-2: Relationship between subcarrier spacing and time duration.

In an OFDM system, using CP mitigates the effects of channel delay spread and intersymbol interference (ISI). CP provides a buffer to protect the OFDM signal from ISI by repeating the end of the symbol at the start of the same symbol. Although using CP reduces the achievable data rate, it eliminates ISI up to the length of the CP. In 5G NR, as subcarrier spacing changes, CP length scales to adapt to the channel conditions.

Channel state information (CSI), which refers to the known properties of a communication link, helps with 5G NR beamforming reliability. 5G NR specifies a new beam management framework for CSI acquisition to reduce coupling between CSI measurements and reporting to control different beams dynamically. CSI uses channel estimation to intelligently change the precoding and adapt the beam to a specific user. The better and more precise this CSI information, the better the link adaptation. CSI is also used for other purposes like equalization to adjust for frequency-depended variations within the transmit (Tx) channel.

Greater throughput

5G boosts throughput in multiple ways. For example:

- » Wider overall channel bandwidths enable sending more data through the air interface.
- » Spatial multiplexing sends multiple independent streams of data through multiple antennas at a given time and frequency and uses enhanced channel feedback.

Enhanced channel feedback improves throughput because the signal is optimized for transmission with advanced channel coding. Massive multiple-input/multiple-output (massive MIMO) and beam-steering technologies improve throughput.



REMEMBER

Operating at mmWave frequencies introduces new challenges in path loss, blockage, and signal reflections. Beam steering is a key technology to overcome these issues. NR specifies new initial access procedures to ensure alignment of the directional transmissions used in beam steering. New initial access techniques use beam sweeping to have the base station transmit multiple beams and then identify the strongest beam and establish a communication link. Validating initial access, beam management, and throughput achieved through the wireless link are key factors for successful beam steering implementation in 5G (see Figure 1-3).

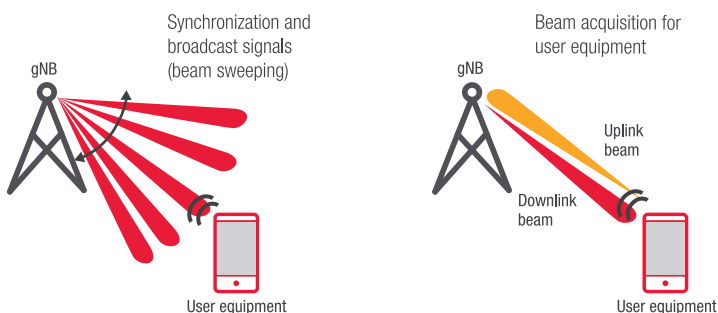


FIGURE 1-3: Beam sweeping and initial access concepts.

Evolution to Release 16

The 5G NR standard continues to evolve with many new enhancements added in Release 16 (Rel-16) including:

- » **URLLC:** Downlink and uplink enhancements, new prioritization and multiplexing, and multiple active configurations help achieve lower latency, higher reliability, and support for new use cases like motion control for factory automation and remote driving, and enhance Rel-15 use cases like AR/VR.
- » **Multi-access edge computing (MEC):** Enabling lower latencies by moving things closer to the edge of the network, MEC is especially helpful for robotics, mission-critical autonomous factories, and remote driving applications. In addition to protocol enhancements, Rel-16 implements redundancy mechanisms and introduces a new intermediate session management function (I-SMF) node to control the user plane function (UPF) when the SMF isn't able to.
- » **Wireless/wireline coexistence:** New nodes improve interworking with non-3GPP systems for wireline access connectivity. Rel-16 adds support for trusted non-3GPP systems and the simultaneous usage of 3GPP and non-3GPP systems.
- » **Interference management:** Cross link interference (CLI) assesses and mitigates DL and UL cross-interference between cells and UEs on the network. Remote interference management (RIM) helps the network understand and mitigate environmental (that is, atmospheric) issues.
- » **MIMO:** New features and enhancements include support for multi-user MIMO (MU-MIMO) that increases capacity by allowing more UEs on the network, DL and UL control signaling for multi-beam operations to reduce latency and signaling overhead, and UE power enhancements.
- » **Power efficiency:** PDCCH lets a UE know when it needs to become active and when it can go inactive (or into sleep mode). MIMO layer adaption allows a UE to turn off unused receivers for longer periods of time to save power.
- » **Unlicensed spectrum:** Rel-16 enables NR to operate in unlicensed spectrum through carrier aggregation (CA) with CCs in licensed and unlicensed spectrum, dual connectivity (DC) with LTE in licensed spectrum and NR in unlicensed spectrum, full NR operation in unlicensed spectrum, and NR cell with DL frequencies in unlicensed spectrum and UL frequencies in licensed spectrum.

Smoothing the Migration Path to the 5G Vision

Network operators are taking different paths to migrate to 5G. The first networks and devices used 5G non-standalone (NSA) mode to accelerate deployment. Now that the standard for 5G standalone (SA) is complete, parts of the industry are moving to 5G SA. Sub-6 GHz 5G deployments are well underway across the globe while mmWave networks are ramping up. Operators are also looking to adopt open, virtualized, and cloud-based radio access networks (RAN) for greater network flexibility and save costs. These evolutions are at the heart of the mobile network evolution.

From 5G NSA to SA

5G can operate in NSA mode — using the existing 4G LTE radio and evolved packet core (EPC) network and eNodeB (eNB) as an anchor and control plane — or in SA mode — using 5G NR and connecting directly to the 5G next-generation core (NGC), operating independently of 4G (see Figure 1-4).

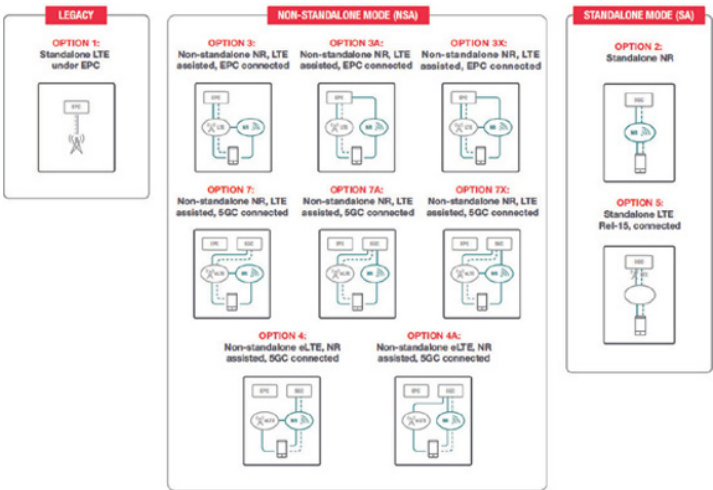


FIGURE 1-4: 5G NR deployment options.



5G NR works alongside 4G and even utilizes the 4G core network for both data and control planes in NSA mode. 5G, 4G, and Wi-Fi need to coexist on the same carriers and utilize unlicensed bands to increase capacity below 6 GHz. Chapter 4 discusses 5G NSA and SA in greater detail.

From FR1 to mmWave FR2

Spectrum harmonization across regions is limited. It's challenging for designers to deliver the full range of capabilities and coverage for consumers around the world. 5G NR specifies frequencies up to 52.6 GHz, and so far, 3GPP has specified associated behavior and performance to open up almost 10 GHz of new spectrum, as follows:

- » **Frequency range 1 (FR1):** 410 MHz to 7.125 GHz adds 1.5 GHz of new spectrum in frequency bands: 3.3–4.2 GHz, 3.3–3.8 GHz, 4.4–5 GHz, and 5.925–7.125 GHz.
- » **Frequency range 2 (FR2):** 24.25 to 52.6 GHz initially added 8.25 GHz of new spectrum in frequency bands: 26.5–29.5 GHz, 24.25–27.5 GHz, and 37–40 GHz.

FR1 introduces new challenges for designs — especially in the new bands above 3 GHz — due to additional propagation loss, the complexity of the test cases, coexistence issues, and the required validation of massive MIMO designs over the air.

Similar to LTE, CA provides larger bandwidths, up to a maximum bandwidth of 800 MHz at FR2. (CA is also applicable to FR1 frequencies although it increases complexity enormously.) Each country decides on the amount of spectrum deployed. New frequency bands are defined and more CA combinations specified.

From traditional RAN to O-RAN

The desire for wireless operators to move their networks from physical purpose-built hardware to virtual and cloud-based software implementations emerged with 4G. This step to virtualization is well underway for the core network. The O-RAN Alliance is working to achieve this goal for the RAN.

The group is specifying the discrete elements of a disaggregated base station in the RAN and is standardizing interfaces between them to allow hosting on white-box hardware instead of purpose-built appliances. This not only allows for easier virtualization of the digital elements of the architecture, but it also opens the door for operators to work with a multitude of vendors that excel in their area of focus. Each subcomponent of Open Radio Access Network (O-RAN) — even pieces within subcomponents — can come from a different vendor.

Read Chapter 3 to find out more about O-RAN.

- » Looking at device development, conformance, and acceptance
- » Accelerating time to market in device manufacturing
- » Maximizing performance in the base station

Chapter 2

Stepping Up 5G Device and Base Station Development

It's an exciting time to be in the wireless industry. The race is on to deploy 5G. New chipsets, devices, and base stations need to be rolled out at the right cost and time. In this chapter, you find out how to accelerate time to market across your product development life cycle.

Integrating and Optimizing 5G Devices

5G introduces new challenges related to the use of millimeter-wave (mmWave) frequencies and beam management, driving the need for validating complex, integrated next-generation devices in over-the-air (OTA) test environments. Use cases for 5G also continue to evolve, which means 5G devices need to be characterized and validated to comply with developing 3rd Generation Partnership Project (3GPP) New Radio (NR) specifications and mobile operator acceptance plans.

These sections discuss the key stages of the 5G device workflow from development to acceptance.

Device development

Every new device carrying a 5G chipset comes with a list of tests. 5G mobile devices also combine sub-6 gigahertz (GHz) bands with new multiple-input/multiple-output (MIMO) antenna systems and mmWave bands with beam steering. Global spectrum assignments and deployment options expand the test matrix.

A comprehensive suite of tools can help you accelerate your device development cycle — pre-silicon, modem and radio frequency (RF) bring-up, mobile test platform, device integration, and performance optimization — across the protocol, RF, and functional and performance test domains.

Device conformance

Passing conformance and device acceptance tests is a significant challenge for 5G device and base station companies.



REMEMBER

Keep the following in mind when preparing for 5G NR conformance tests:

- » Conformance test requirements and test methods continue to evolve as 3GPP refines and adds to the standards.
- » Frequency range 2 (FR2: 24.25 to 52.6 GHz) significantly increases test complexity.
- » You can expect exponential growth in the number of test cases.

Preparing for conformance tests by performing pre-conformance testing is critical. 5G NR introduces new test challenges due to incomplete test requirements, new mmWave operating bands, more complex tests, and standards that continue to evolve. Companies that prepare for conformance and device acceptance tests accelerate their time to market.



TIP

Although the standards progress constantly, testing of 5G products has been ongoing for years. Chipset and device makers must carefully select test equipment for conformance testing, keeping potential for upgrades in mind.

Device acceptance

5G technology needs to address a wide range of new use cases. Accelerating device certification and acceptance requires early and continuous access to the latest 3GPP conformance and mobile network operator (MNO) acceptance tests.

5G device acceptance solutions span the entire workflow — design validation, pre-conformance, conformance, regulatory, and carrier acceptance — and cover the protocol and RF/radio resource management (RRM) domains.

ACCEPTANCE TESTING HELPS MNO GRAB EARLY LEADERSHIP IN 5G

In the summer of 2018, a major MNO began collaborating with Keysight on 5G network design, development, and testing. The primary goal of the collaboration was 5G device conformance testing. Conformance testing ensures that mobile devices adhere to industry standards and regulatory requirements. Those requirements include protocol and RF, with measurements such as occupied bandwidth, receiver performance, intermodulation distortion, and RRM.

Timing was critical. The MNO was preparing to roll out 5G services in early 2019. It needed to conduct testing on early 5G smartphones and other devices in the fall of 2018. At the time, the 3GPP conformance test requirements and test methods were less than 50 percent complete. The MNO needed to develop test specifications and provide test case scripts for its device acceptance test plans to ensure the interoperability of the devices it was planning to launch with its 5G network.

It needed a partner with experience in 5G device testing. In addition to the evolving nature of 5G standards and test requirements, 5G conformance testing is complicated by a dramatic increase in complexity compared with 4G LTE. Issues include higher frequency ranges, wider channel bandwidths, and increasing coexistence scenarios. Test environments and test schemes are also different between frequency range 1 (FR1, 410 MHz to 7.125 GHz) and frequency range 2 (FR2, 24.25 to 52.6 GHz). The number of test cases for 5G represents an exponential increase compared with LTE.

(continued)

(continued)

Solutions

Keysight has invested heavily in 5G. It partnered early with standards-setting industry leaders to understand the complexities of 5G and develop solutions that span the entire device development workflow. Keysight is also a contributor to 3GPP, helping define 5G specifications and test cases. Although mmWave is new to MNOs, Keysight has mmWave expertise from decades of experience in aerospace and defense. The MNO chose Keysight based on that expertise, coupled with Keysight's compelling 5G road map and commitment to collaboration.

Working with Keysight, the MNO realized the value of investing in a 5G test system that could handle protocol, RF, and RRM testing. The MNO ultimately chose to leverage Keysight's portfolio of Network Emulation Solutions (NES) built on the E7515B UXM 5G Wireless Test Platform, including Keysight's:

- S8701A Protocol R&D Toolset
- S8704A Protocol Conformance Toolset
- S8705A RF/RRM DVT & Conformance Toolset

Results

Following the engagement with Keysight and the rollout of its 5G network, the MNO became an early leader in 5G. Thanks in part to its collaboration with Keysight on device acceptance testing, the MNO was able to launch 5G services commercially in the spring of 2019. Within five months, the MNO had amassed more than 1 million 5G mobile subscribers, becoming the first MNO in the world to achieve this milestone. In addition to mobile data subscriptions, the MNO has successfully launched focused 5G services in areas such as smart factories, smart media, virtual reality, and augmented reality.

Ramping Up Device Manufacturing

5G brings new opportunities for device manufacturers but also introduces significant challenges associated with accelerated timelines and high technical complexity.



TIP

To keep up with the demand for high-volume manufacturing of 5G devices, manufacturers need to accelerate their time to market and reduce testing cost. Key strategies to implement include the following:

- » **Multi-device testing:** Testing multiple devices at the same time is critical to increase production capacity and reduce the cost of test. Device makers can use parallel device testing to push the concept to its limits by using instrumentation designed for multi-device testing.
- » **Adopting a common measurement science:** Many device makers adopt a siloed approach to device development and test, missing out on the time-to-market efficiencies they could gain by adopting a common measurement science across the device workflow.
- » **Leveraging high-performance instrumentation:** Testing each device faster is another strategy device makers can use to accelerate the testing process and increase their production output while reducing the cost of test. Instrumentation featuring quad-core controllers and leveraging a high-speed backplane provides ultra-fast data processing. Advanced sequencing techniques and single-acquisition multiple measurements help accelerate test execution.
- » **Deploying flexible test equipment:** Device manufacturers need to control the costs of acquiring test assets and operating the assets over their useful life. Modular test platforms and software licenses help control capital and operational expenditures.
- » **Utilizing financial services:** Device manufacturers need to adjust test capacity quickly and easily and modify their manufacturing test operations to meet volume goals and target dates while conserving capital. Operating leases provide instant access to leading technologies with a lower impact on budgets.

Optimizing gNB Performance

5G NR is being deployed around the world to deliver faster data rates and unprecedented reliability to wireless communications. New base station types have emerged, defined according to the frequency range and the antenna configuration of the equipment.



REMEMBER

5G base stations are called gNodeB (gNB) and fall into three categories:

- » **C** refers to base stations with antenna connectors.
- » **O** refers to units with no antenna connectors.
- » **H** refers to units that use a hybrid approach with some antenna connectors accessible in the system between modules and an integrated antenna in the base station assembly.

The industry uses numerals to denote the frequency range, FR1 (410 MHz to 7.125 GHz) or FR2 (24.25 GHz to 52.6 GHz). Type 1-C base stations are tested using a conducted approach, like 3G and 4G base stations, but all the testing for O units must be done over the air in a radiated type of test. A 5G base station needs to support an increasing number of channels for applications like spatial multiplexing and beamforming. The level of integration is also increasing, even in FR1. The market is moving toward more type 1-O base stations.



REMEMBER

Conformance testing requires a good understanding of 3GPP specifications. 3GPP technical specification (TS) 38.104 and 38.141 are essential documents. The tests are organized into chapters, with Chapter 6 covering transmitter characteristics, Chapter 7 covering receiver aspects, and Chapter 8 covering receiver performance. In addition, Chapter 4 is important because it covers the manufacturer's declarations that define base station types, classes, and other important aspects, and each test case has a unique signal configuration derived from the manufacturer's declaration. Using test solutions that facilitate the interpretation of 3GPP specifications, simplify the test setup, and automatically generate test plans helps speed up conformance testing significantly.



TIP

Network equipment manufacturers (NEMs) need to accelerate the workflow from R&D, integration, and design verification to manufacturing test for high-performance mmWave base stations and small cells. Evolving 3GPP standards expand the complexity of the physical layer while adding OTA test requirements for mmWave bands. A common graphical user interface (GUI) and software facilitates high asset utilization and a fast transition from R&D to design validation and manufacturing. Solutions that serve all bands also save space and reduce support and maintenance costs.

- » Enabling service agility
- » Implementing O-RAN

Chapter 3

Accelerating the Transformation to O-RAN

5 G is a key driving force behind the migration to Open Radio Access Networks (O-RAN). Network densification increases exponentially with 5G, and mobile operators need to adopt standards-based networks to improve resource utilization. In addition, the existing network infrastructure and traditional fronthaul technologies are less able to address the increased demand, flexibility, and bandwidth coming with 5G. To evolve to 5G, mobile network operators (MNOs) need O-RAN. This chapter discusses O-RAN initiatives, opportunities, and challenges.

Overcoming Traditional RAN Challenges

Service agility requires moving new services into production quickly. Proprietary components and interfaces in a traditional RAN limit service agility. By virtualizing services into network functions and using cloud-scale operators that provide flexibility at a lower cost, operators can achieve service agility and cloud-scale economics. This is the goal of O-RAN.

The O-RAN Alliance is a group formed in February 2018 by five global operators to define the next-generation radio access network (RAN) architecture. The organization defines the specifications, reference architecture, and interfaces between the various subcomponents that form the O-RAN.



REMEMBER

The O-RAN Alliance has adopted two core principles:

- » **Openness:** With O-RAN, operators can work directly with radio frequency (RF) contract manufacturers, companies that specialize in graphics processing units (GPUs) and field programmable gate arrays (FPGAs), and virtual cloud infrastructure providers. They can mix and match components and work with specialists to create powerful and unique solutions. O-RAN increases competition in the ecosystem to the operators' advantage while embracing open-source software.
- » **Intelligence:** 5G generates a significant amount of data, making it humanly impossible to analyze it and take corrective actions on the network — whether it be to add capacity or deploy certain services in specific regions — in a timely manner. With its multiple interface points, O-RAN promotes the use of AI and machine learning (ML) to collect data, perform analysis, and feed information back to the network in an automated fashion. Self-driving networks will deliver a significant reduction — 40 to 50 percent, according to various studies — for network service providers.



TECHNICAL
STUFF

The O-RAN Alliance is the result of a merger between the Virtualized Radio Access Network (xRAN) Initiative and the Centralized Radio Access Network (C-RAN) Alliance, whose purpose was to define virtualized RANs.

It includes nine working groups, each focused on a specific area, as follows:

- » **WG1: Use cases and overall architecture.** Identify the use cases and requirements and plan the overall architecture of O-RAN and proof-of-concepts.
- » **WG2: RAN intelligent controller (RIC), non-real-time (non-RT) aspects, and A1 interface.** Specify the artificial intelligence (AI) enabled RIC (non-RT) functionality for operational supervision, intelligent radio resource management

(RRM), and A1 interface (used between the orchestration/network management system [NMS] layer with non-RT RIC and eNodeB [eNB]/gNodeB [gNB] containing near-RT RIC).

- » **WG3: RIC, near-RT aspects, and E2 interface.** Specify the RIC (near-RT) architecture that enables control and optimization of RAN elements and resources via the E2 interface (used between the non-RT RIC and central unit [CU]/distributed unit [DU]).
- » **WG4: Next-generation fronthaul interface (NGFI) specification.** Specify the open fronthaul interface (NGFI-I) between the DU and the active antenna unit (AAU) based on C-RAN and xRAN's work.
- » **WG5: Key interfaces and stack reference design.** Focus on the design of the open CU, RAN virtualization, and splits with the interfaces intersecting with 3rd Generation Partnership Project (3GPP) specifications.
- » **WG6: Cloudification and management and orchestration (MANO) enhancement.** Specify the virtualization layer and hardware, decoupling of virtualized network functions (VNF) and NFVI, and MANO enhancements.
- » **WG7: White-box hardware.** Specify and release a complete reference design to foster a decoupled software and hardware platform.
- » **WG8: Stack reference design.** Develop the software architecture and release plan for the O-RAN central unit (O-CU) and O-RAN distributed unit (O-DU) based on the O-RAN and 3GPP specifications.
- » **WG9: Open x-haul transport.** Focus on the transport domain consisting of the transport equipment, physical media, and control/management protocols associated with the transport network underlying the assumed Ethernet interfaces (for fronthaul, mid-haul, and backhaul).

In addition, the Test and Integration Focus Group (TIFG) is responsible for defining the overall approach for testing and integration. TIFG is working with the O-RAN Test Integration Center (OTIC) to establish centers around the world for O-RAN components compliance certification.

The founding members of the O-RAN Alliance were all network operators (AT&T, China Mobile, Deutsche Telekom, NTT DOCOMO,

and Orange), but they enabled many new entrants. In addition to MNO members (34 as of July 2021), more than 210 other contributors are now involved, including network equipment manufacturers (NEM), chipset vendors, and companies that build stacks and radio elements. Operators can also select software from various vendors to use their preferred solution for each function.

Understanding O-RAN Basics

RAN deployment for 4G and earlier generations relied heavily on closed proprietary network hardware and software from the same vendor. O-RAN breaks down the traditional hardware-centric RAN into building blocks and connects them using open and standardized interfaces.



REMEMBER

Here are the main components of an O-RAN network:

- » **O-RU:** Refers to O-RAN radio unit (O-RU). Performs the fast Fourier transforms (FFT), some beamforming, and precoding.
- » **O-DU:** Handles the media access control (MAC), radio link control (RLC), and high physical (H-PHY) layers.
- » **O-CU:** Handles the packet data convergence protocol (PDCP) layer between the network and the user equipment (UE).
- » **RIC:** Includes the non-RT RIC and RT RIC that gather information from the O-DUs, O-CUs, and O-RUs; perform analytics; and use AI and ML to generate suggestions for these network elements to optimize the RAN.

The fronthaul is the connection between the baseband unit (BBU) and remote radio head (RRH). It becomes much more challenging with 5G. A lot more data needs to go back and forth because of higher bandwidths and more antenna ports using massive multiple-input/multiple-output (massive MIMO) technology, leading to the use of the following solutions in O-RAN:

- » **High-level split (HLS):** Splits the higher layer between the DU and the CU.
- » **Low-level split (LLS):** Splits the lower layer between the RU and the DU.

With O-RAN, the O-RU sits at the edge, the O-DU sits in the middle and performs some of the processing, and the interfaces are standardized. Operators can use different vendors for the CUs, DUs, or RUs because the components are much more interoperable, and the protocols are clearly defined. But 5G brings about a bandwidth explosion in the fronthaul that requires a new interface between the BBU and the RRH. The enhanced Common Public Radio Interface (eCPRI) interface reduces the bandwidth requirements by moving all the physical (PHY) layer functionality to the RUs, but RU complexity increases tremendously. That's where the functional splits (see Figure 3-1) come in.

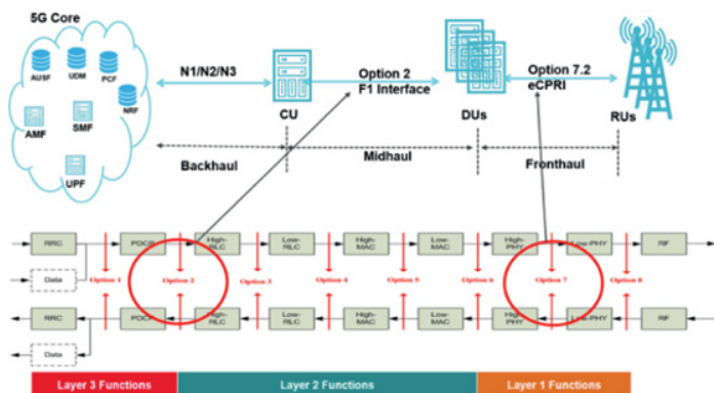


FIGURE 3-1: 5G functional splits.

Option 8 is a split option that puts all the PHY layer functionality into the DUs, keeping only the antennas at the edge.

But because the bandwidth requirements increase significantly with 5G, even a nominal scenario requiring 200 or 300 gigabits of transport between the DUs and RUs is untenable. Option 7.2 provides an optimal split between the DUs and RUs. The PHY layer is divided into low-PHY and high-PHY: The low-PHY stays in the RUs and the high-PHY stays in the DUs.

Moving from the DUs to the CU typically means an upper layer split or HLS (Option 2). Processor-intensive functionality moves to the CU while the remaining part of the stack — such as the MAC and RLC layers, along with the high-PHY — stay in the DUs. You can split at the control level with an interface between the DUs and the CU.

Addressing conformance and integration challenges

While providing greater flexibility in how networks are built, O-RAN also represents a paradigm shift for operators. Until now, a base station was a single entity coming from a single network vendor, so it was tested as a unit. With O-RAN, the base station consists of different components coming from different vendors; even subcomponents may come from different suppliers.



REMEMBER

MNOs need to put these various elements together and ensure that the components they source from different vendors work together seamlessly. Components need to both interoperate and conform to the specifications. Performance is also a key area of focus to control the amount of bandwidth between the O-DUs and the O-RUs.

Many aspects must align between the DUs and the RUs for the whole system to work. The good news is that solutions are available to overcome these challenges, and more will emerge.



REMEMBER

The migration toward more open fronthaul interfaces comes with many challenges. You'll need to test more units and perform peer emulation between all the O-RAN components. You'll also need to conduct conformance, interoperability, and performance testing for all these components.

Deploying O-RAN

The conversation around O-RAN has shifted from whether the technology is commercially viable to discussions of when, where, and how to deploy O-RAN. Several operators have started O-RAN deployments, including Rakuten Mobile, Dish Network, and Vodafone. Deloitte Insights estimates that there were 35 active Open RAN deployments worldwide at the end of 2020.

In the deployment phase, verifying O-RAN network performance from the user perspective is essential. Having multiple UEs successfully attach and send/receive data from/to the network is one of the most important network verification tests.



TIP

Data tests help measure the capacity and quality of service of the O-RAN network. You'll need to perform downloads, uploads, data transfers, and ping tests as well as record and analyze 5G NR signal parameters, radio resources, latency, and different layer throughputs to optimize the network.

- » Moving to 5G standalone (SA) networks
- » Living on the edge with multi-access edge computing (MEC)
- » Looking at 5G observability challenges
- » Ensuring 5G device and network security

Chapter 4

Advancing Virtualization, Cloudification, and MEC

In this chapter, you explore the role of virtualization, cloudification, and multi-access edge computing (MEC) in helping mobile network operators (MNOs) evolve to intelligent, open networks and the new observability and security challenges brought by these technologies.

Evolving from 5G NSA to SA

The first rollout of 5G networks are non-standalone (NSA) deployments that focus on providing higher data bandwidth and reliable connectivity for enhanced mobile broadband (eMBB) use cases. This rollout is in line with the 3rd Generation Partnership Project (3GPP) specification that encourages early deployments of 5G networks and devices under NSA operation to accelerate deployments.



REMEMBER

A 5G NSA environment only requires upgrading the 5G radio access network (RAN) because it uses the 4G core, known as evolved packet core (EPC). MNOs who wanted to be the first to offer 5G speeds to their subscribers started with NSA and planned to implement 5G standalone (SA) once the standard was ready and the technical complexity of managing 4G and 5G in the same physical space was addressed.

Most operators opting to deploy NSA first choose 5G NSA option 3X (NSA3X). This option allows different types of user equipment (UE) to connect to the network, but it can't deliver many 5G capabilities. Dual connectivity (DC) also reduces UE battery life. MNOs move to 5G SA by introducing the 5G core (5GC) network in parallel to the EPC network. They can transition to 5G SA via several options including option 2 (SA2), 5 (SA5), and 7 (SA7), with most opting for SA2. (Refer to Chapter 1 for more details, including a figure about 5G NR deployment options.)

But operators are increasingly going straight from 4G to 5G SA. 5G SA deployments are accelerating as the market matures, network infrastructure elements for 5G SA become more available, and operators want to deliver new services leveraging network slicing. Network slicing enables operators to “slice” their network architecture into multiple networks to meet specific service requirements for latency, reliability, mobility, and throughput.

Embracing MEC

MEC delivers cloud computing capabilities and an IT service environment at the edge of the cellular network. It allows compute resources to be deployed closer to the edge of the network, in effect *transporting* cloud capabilities to the edge to overcome latency and network reliability issues.

MEC offloads client-compute demand given the higher available communication bandwidth from the client. It allows for lower demand on the network for predictable compute demands by placing them closer to the client. It can also be used to optimize the network function itself, because of its large, distributed compute capability.

MEC also allows for greater flexibility in applications. For example, applications can be architected to run in the client, on the edge, in the cloud, or split across multiple domains to optimize performance, power consumption, and other aspects.



REMEMBER

MEC enables offloading traffic at the edge, saves network bandwidth, and makes achieving latency requirements possible.

Enabling 5G Observability

With 5G and Open Radio Access Network (O-RAN), the number of interfaces in mobile networks increases greatly, and there is room in the specifications for interpretation. These factors increase the need for more precise data correlation and analytics.

While the 3rd Generation Partnership Project (3GPP) specifies the RAN interfaces, the O-RAN Alliance, which develops the O-RAN specifications, also adds new interfaces to open the mobile network at different points and provide flexibility in implementation. Operators need to tap into a lot more points to get the information they're looking for.



TECHNICAL
STUFF

Some of the open interfaces the O-RAN Alliance works on are the following:

- » **A1:** Interface used between the orchestration/network management system (NMS) and the 4G or 5G base station
- » **O1:** Interface that connects the orchestration/NMS to the O-RAN network elements
- » **E2:** Interface used between the non-real-time RAN intelligent controller (non-RT-RIC) and the O-RAN distributed unit (O-DU)/O-RAN central unit (O-CU)
- » **F1:** Interface used between the O-DU and the O-CU
- » **X2:** Interface used between 4G base stations and the 5G base station called gNodeB (gNB)
- » **Xn:** Interface used to pass control and user plane information between gNBs, 4G base stations capable of communicating with gNBs, or both

The growing number of interfaces increases the data flow in the network that needs to be observed. More splits of the protocol stacks also increase the need for data correlation and analysis. Filtering/correlation capabilities for nodes (combination of multiple network elements) for the network end to end (E2E) are also needed.

Chapter 3 covers the different O-RAN network elements and the functional splits in greater detail.

Ensuring Security

With 5G, networks become increasingly distributed, and more components move to the edge of the network, creating the need for better security. Massive IoT increases the number of devices at the network edge exponentially.



WARNING

According to the June 2021 *Ericsson Mobility Report*, by 2026 there will be 5.4 billion cellular IoT connections — more than three times the amount of cellular IoT connections in 2020.

Security requirements for network infrastructure, devices, and consumers increase massively with 5G. 5G also needs to fill the security gaps from previous generations of cellular technology in user authentication and data encryption.

5G brings two key security enhancements:

- » Location-based subscriber authentication to only allow real subscribers to access network services
- » Security-level adaptation with network slicing to increase the level of security for specific virtual networks or services

Leveraging cryptography, 5G will deliver a higher level of security among mobile networks from different MNOs and control access to network services. Stronger encryption (256-bit algorithms versus 128-bit in 4G) will also help 5G networks address potential attacks from quantum computers.

- » Realizing the 5G opportunity
- » Looking to the future with 6G

Chapter 5

Expanding Wireless Connectivity to Enable Innovation

In this chapter, you explore the endless possibilities of 5G: new services, new industries, and new revenue streams. You also get a glimpse of the future — 6G.

Recognizing New Opportunities

5G networks deliver faster and more reliable communications. They open doors to exciting new opportunities, including the Internet of Things (IoT), autonomous vehicles, fixed wireless broadband, and faster video viewing, to name a few. The following sections take a closer look at them.

New services

5G expands the portfolio of services that mobile network operators (MNOs) can offer consumer and business customers. Some

examples of new consumer services enabled by 5G include the following:

- » Enhanced video leveraging 4K, 8K, and 360-degree formats
- » Live streaming sports and entertainment
- » Vehicle connectivity and entertainment
- » Music and gaming applications

For business customers, 5G enables new services such as the following:

- » Smart factory automation and safety applications
- » Remote mining, drilling, and other hazardous operations
- » Connected vehicle fleets
- » Remote health diagnostic services

New industries

Smart homes, smart cities, and multiple industries (such as health, retail, smart grids, and remote factories) have a common thread — they're using more and more devices and sensors that communicate with one another and the rest of the world.

Many of these devices are mission critical, whereas others may send high-definition video, requiring high availability and very low latency. Yet another set of devices may send small data packets relatively infrequently (for example, every few hours, days, or weeks). Some examples of new industry use cases that are emerging with 5G include the following:

- » **Industrial applications:** Groups like the 5G Alliance for Connected Industries and Automation (5G-ACIA) are working to help manufacturing, mining, petroleum, and other industries to leverage wireless connectivity that is now more reliable with lower latency than in previous wireless generations, replacing wired connections and improving operational efficiency and flexibility. Private networks enable factories and other enterprises to operate dedicated, on-site networks to improve efficiency, manage capacity, and maintain security. Applications include advanced predictive maintenance to reduce equipment downtime, precision

control and monitoring to increase machines' range of motion, and AR to enable humans to manage specific tasks remotely.

- » **Logistics and freight:** These devices and sensors typically require lower data rates but need wide coverage and reliable location information.
- » **Smart grid:** A smart grid requires low-latency sensors to regulate the use of utilities such as electricity, natural gas, and water. Leveraging digital information, such as the behaviors of suppliers and consumers, allows the smart grid to improve the efficiency, reliability, economics, and sustainability of the production and distribution of these resources.
- » **Remote medical:** Collaborating on a medical case with other surgeons located thousands of miles away was a use case scenario discussed as part of the 4G Long Term Evolution (LTE) rollout. It can become a reality with the extreme bandwidth, low latency, and high availability of 5G networks.
- » **Hazardous areas:** The ability to remotely explore mining areas or shut down a nuclear power plant during an emergency — in a fraction of the time required for human interaction, and without risk to human life — is possible with 5G.

New revenue streams

5G will enable new revenue streams for MNOs, device manufacturers, service providers, and many other enterprising ventures. Fixed wireless access (FWA), real-time and near-real-time entertainment services, augmented reality (AR) and virtual reality (VR) applications, and autonomous vehicles are just a few examples.

Defining the 6G Vision

6G will enable exciting new use cases above and beyond those available with 5G. In addition to the next-level evolution in autonomous driving and smart manufacturing, 6G will enable innovative applications by combining sensing, imaging, and precise timing with mobility, and by truly leveraging artificial intelligence (AI)

and intelligent networks. By further integrating communications technologies into society, 6G technology will bring mixed-reality experiences and immersive telepresence to life, while playing a pivotal role in achieving global sustainability, improving society, and increasing productivity across industries.

However, ubiquitous wireless intelligence requires engineering 6G technology to deliver much higher performance than 5G with capabilities measured not only in updates to existing key performance indicators (KPIs), but also in new KPIs driven by the uniqueness of the 6G vision. Early 6G targets represent a 10–100x increase over 5G for KPIs such as peak data rates, latency, and density. 6G also increases the importance of KPIs related to jitter, link budget, and other technology aspects (see Figure 5-1).

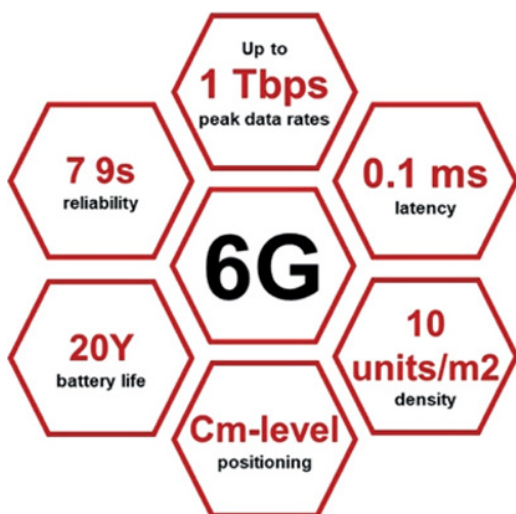


FIGURE 5-1: 6G targets.

The need for wider bandwidths will require the use of frequencies above 100 gigahertz (GHz) to enable ultra-high data-rate short-range networks. Precise timing requirements will bring time-engineered networks and new applications but will also require changing the way networks operate. Delivering on 6G targets will demand significant advances in computing and networking architectures, chipset designs, and materials.

Privacy and security concerns will get increased focus on all network layers, including new focus on physical (PHY) layer security. The use of AI will also be fundamental to optimize network operation, fight attacks, and facilitate recovery. A digitized, data-driven society with instant and unlimited wireless connectivity will lead to continued exponential growth in data traffic and connections and will demand a hyper-flexible network. These aspects will bring spatial spectral efficiency and connectivity challenges.

Extreme modulation bandwidths, ever-shorter wavelengths, and higher propagation and atmospheric loss in the sub-terahertz (THz) and THz spectrum will require reduced beamwidth and increased antenna and device integration. Radio resource optimization and intelligent networking will also require innovation in radio frequency (RF), baseband, and system design to reduce power consumption.



REMEMBER

Significant technical challenges lie ahead for wireless design and test engineers. 6G is in its infancy and will require years of research, but wireless communications technology evolves fast. As 5G is being built, the industry needs to prepare for 6G.

- » Addressing standards, regulations, network, and security requirements
- » Conducting device performance tests
- » Testing your air interface in the field
- » Using real devices on your network to ensure high quality of experience (QoE)

Chapter 6

Ten Steps to 5G Deployment Success

This chapter identifies ten steps you must take in order to help ensure 5G deployment success for your organization.

- » **Step 1: Ensure that devices meet 3rd Generation Partnership Project (3GPP) standards, industry regulations, and your network requirements.** Each release of the 5G standard introduces new capabilities that require new technologies. Ensure that your devices meet 3GPP standards, as well as any relevant industry regulations and your unique network requirements.
- » **Step 2: Assess the cybersecurity hygiene of 5G devices.** The attack surface grows exponentially with billions of connected mobile devices, Internet of Things (IoT) devices, and Wi-Fi networks and endpoints. Assess the cybersecurity posture of your 5G devices thoroughly and frequently.
- » **Step 3: Verify device connectivity performance for an optimal user experience.** 5G devices will access different radio access technologies (RATs), including 5G New Radio (NR), 4G Long Term Evolution (LTE), and Wi-Fi. Operators need to evaluate real-world performance and handovers

between radio networks. This real-world evaluation is known as the *inter-RAT handover test*.

- » **Step 4: Check that radio access network (RAN) elements conform to specifications.** Before release into the market, all 5G devices and base stations must meet a minimum level of performance. 3GPP and the O-RAN Alliance define what and how to measure for compliance against the core specifications.
- » **Step 5: Perform interoperability testing for seamless interaction.** Open Radio Access Network (O-RAN) brings the disaggregation of 5G base stations into various elements. Validating interoperability and performance against expected use models helps ensure seamless interaction.
- » **Step 6: Stress your RAN and core networks with 5G traffic.** Ensure that your RAN and core networks meet your high performance, low latency, and robust reliability requirements under load.
- » **Step 7: Ensure that your infrastructure runs in a virtual, cloudified environment.** To migrate from 5G non-standalone (NSA) to standalone (SA), you need to take advantage of network functions virtualization infrastructure (NFVI) and virtualized network functions (VNF), using virtualization, containerization, and cloud technologies.
- » **Step 8: Measure and analyze the air interface in the field.** The physical layer standards in 5G NR Release 15 and beyond define a flexible air interface to support the many use cases expected in 5G. Field test your air interface to ensure that it performs as expected.
- » **Step 9: Test your network with real devices to assess performance.** Stress test your network with 5G user equipment (UE) traffic under different use case scenarios to ensure that it meets key performance metrics like high data throughput, reliability, and low latency.
- » **Step 10: Observe 5G traffic to ensure high QoE for subscribers.** 5G and O-RAN increase the number of interfaces in mobile networks, and the specifications leave room for interpretation. Ensure complete observability using precise data correlation and analytics.

Glossary

3rd Generation Partnership Project (3GPP): A mobile communications industry collaboration that organizes the development and management of mobile communications standards.

5G New Radio (NR): Shorthand for 5G NR, the standard for a new orthogonal frequency-division multiplexing (OFDM) based air interface designed to support 5G devices, services, deployments, and spectrum. NR describes 5G in the same way Long Term Evolution (LTE) describes 4G.

active antenna unit (AAU): An antenna that contains active electronic components such as transistors, unlike an antenna with passive components such as metal rods, capacitors, and inductors.

base station: A fixed communications location that is part of a wireless network. Referred to as “eNodeB” (or eNB) in LTE and as “gNodeB” (or gNB) in NR.

baseband unit (BBU): A component of the base station that handles radio communications and radio control processing functions. The baseband unit converts data into a digital signal and sends it on to the remote radio head (RRH), which then converts it into an analog signal. In a centralized radio access network (C-RAN) architecture, the baseband unit is usually geographically separated from the radio head.

carrier aggregation (CA): A major feature introduced with Long Term Evolution Advanced (LTE-Advanced), enabling mobile network operators to combine multiple carriers in fragmented spectrum bands to increase peak user data rates and the overall capacity of the network.

cellular vehicle-to-everything (C-V2X): A 3rd Generation Partnership Project (3GPP) standard describing a technology to achieve the passing of information between vehicles and roadway infrastructure to facilitate road safety and traffic efficiency.

central unit control plane (Cu-CP): A logical node hosting the radio resource control (RRC) and the control plane part of the packet data convergence protocol (PDCP).

central unit user plane (Cu-UP): A logical node hosting the user plane part of the packet data convergence protocol (PDCP) and the service data adaptation protocol (SDAP).

centralized radio access network (C-RAN): Also called cloud RAN, a radio access network (RAN) architecture that separates baseband functions from antennas and remote radio heads (RRHs), and pools baseband functions in centralized baseband units (BBUs).

centralized unit (CU): Provides support for the higher layers of the protocol stack such as the service data adaptation protocol (SDAP), packet data convergence protocol (PDCP), and radio resource control (RRC) layers.

channel state information (CSI): Refers to known properties of a communication link. 5G New Radio (NR) specifies a new beam management framework for CSI acquisition to reduce coupling between measurements and reporting to control different beams dynamically.

component carrier (CC): One carrier of either Long Term Evolution (LTE) or New Radio (NR). In the context of carrier aggregation, multiple component carriers are aggregated together for an effectively wider bandwidth.

control and user plane separation (CUPS): A foundational concept for 5G networks that enables operators to independently scale the control plane and user plane of the mobile network as needed.

cross link interference (CLI): A reference signal that enables the network to assess and mitigate downlink (DL)/uplink (UL) cross-interference between cells and user equipment (UE).

cyclic prefix orthogonal frequency-division multiplexing (CP-OFDM): An orthogonal frequency-division multiplexing (OFDM) technique that uses cyclic prefixes instead of null guards, protecting OFDM signals from intersymbol interference (ISI).

device under test (DUT): DUT, equipment under test (EUT), system under test (SUT), and unit under test (UUT) are all terms used to refer to a device undergoing measurement procedures.

discrete Fourier transform spread orthogonal frequency-division multiplexing (DFT-s-OFDM): An optional modulation format used in the uplink (UL) in 5G New Radio (NR). DFT-s-OFDM uses the mathematical concept of discrete Fourier transform to encode (spread) digital data on multiple frequency channels in a frequency-division multiplexing scheme, decreasing the peak-to-average-power-ratio (PAPR), and thus decreasing demand on transmit amplifiers. Used in user equipment (UE) UL radio systems. Mandatory in Long Term Evolution (LTE), optional in NR.

distributed unit (DU): Provides support for the lower layers of the protocol stack such as the radio link control (RLC), media access control (MAC), and physical (PHY) layers.

downlink (DL): The path of transmission from the base station to the user equipment (UE). In 5G, the downlink (DL) waveform is orthogonal frequency-division multiplexing (OFDM).

dual connectivity (DC): Carrier aggregation of Long Term Evolution (LTE) and 5G New Radio (NR) carriers. Evolved-universal terrestrial radio access-new radio (EN-DC) enables dual connectivity between NR and LTE/evolved universal mobile telecommunications system terrestrial radio access networks (E-UTRAN). New Radio dual connectivity (NR-DC) enables dual connections that are both NR, including frequency range 1 (FR1) and frequency range 2 (FR2).

enhanced mobile broadband (eMBB): One of three key use cases defined in 5G New Radio (NR), eMBB refers to target 5G peak and average data rates, capacity, and coverage as compared to conventional mobile broadband (MBB). eMBB specifies a 5G design capable of supporting up to 20 gigabits per second (Gbps) in the downlink (DL), and 10 Gbps in the uplink (UL).

evolved node B (eNodeB or eNB): Base station connected to the network that communicates wirelessly with mobile handsets in a 4G Long Term Evolution (LTE) network or 5G non-standalone (NSA) mode.

evolved packet core (EPC): The core network of the 4G Long Term Evolution (LTE) system. The EPC features a flat architecture to handle voice and data efficiently. It requires a few network nodes to be involved in the handling of traffic. EPC serves as an anchor in the initial implementations of 5G NSA systems.

fast Fourier transform (FFT): An algorithm that computes the discrete Fourier transform of a sequence, or its inverse.

field programmable gate array (FPGA): An integrated circuit designed to be configured by a customer or a designer after manufacture.

fixed wireless access (FWA): A type of wireless broadband data communication between two fixed locations and connected through wireless access points and equipment.

frequency range 1 (FR1): One of two frequency ranges prescribed by 5G New Radio (NR). FR1 covers sub-6 gigahertz (GHz) frequency bands, including some used by previous standards. FR1 ranges from 410 megahertz (MHz) to 7125 MHz.

frequency range 2 (FR2): The second of two frequency ranges prescribed by 5G New Radio (NR); FR2 includes the millimeter-wave (mmWave) frequencies and ranges between 24.25 gigahertz (GHz) and

52.6 GHz. Bands in FR2 have a shorter range and higher available bandwidth compared to bands in FR1.

full-dimension multiple-input/multiple-output (FD-MIMO): A MIMO technique added to the 3rd Generation Partnership Project (3GPP) specification in Release 13 that extends MIMO concepts to work in three dimensions: azimuth (horizontal), control (range), and elevation (vertical).

graphics processing unit (GPU): A specialized integrated circuit designed for parallel processing and used for video and graphics rendering.

high-level split (HLS): A gNodeB (gNB) option that splits the higher layer between the distributed unit (DU) and the central unit (CU).

International Telecommunication Union (ITU): A United Nations agency responsible for information and communications technologies. The ITU created the standard that sets forth the requirements for 5G networks, devices, and services.

Internet of Things (IoT): The network of physical objects that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet.

key performance indicator (KPI): A metric that quantifies how mobile phones and other user equipment (UE) perform on a network.

Long Term Evolution (LTE): A standard for wireless broadband communication for mobile devices and data terminals.

Long Term Evolution Advanced (LTE-A): Also known as *LTE Release 10*, LTE-A is one of the two mobile communication platforms officially designated by the International Telecommunication Union (ITU) as the first 4G technology (the other is LTE-Advanced Pro). It specifies data rates of 500 megabits per second (Mbps) maximum upload speed and 1 gigabit per second (Gbps) maximum download speed with a latency (round-trip) of 5 milliseconds (ms).

Long Term Evolution Advanced Pro (LTE-Advanced Pro): Also known as 4.5G, 4.5G Pro, 4.9G, and pre-5G, its feature functionality is defined in 3rd Generation Partnership Project (3GPP) Releases 13 and 14. An evolution of LTE with speeds up to 1 gigabit per second (Gbps), LTE-Advanced Pro incorporates new functionality, including 256 quadrature amplitude modulation (QAM), full-duplex multiple-input/multiple-output (FD-MIMO), LTE-Unlicensed, LTE IoT, and other technologies to evolve existing networks towards the 5G standard.

Long Term Evolution Internet of Things (LTE IoT): Also known as *narrowband Internet of Things (NB-IoT)*, LTE IoT is a 3rd Generation

Partnership Project (3GPP) standard that enables a wide range of cellular devices and services using low-power radio technology.

Long Term Evolution Unlicensed (LTE-Unlicensed): Extension of the LTE wireless standard to offload data traffic in the unlicensed 5-GHz frequency band.

low-level split (LLS): A gNodeB (gNB) option that splits the lower layer between the radio unit (RU) and the distributed unit (DU).

management and orchestration (MANO): Framework for managing and orchestrating virtualized network functions (VNFs) and components.

massive machine-type communications (mMTC): One of three key use cases defined in 5G New Radio (NR), mMTC supports 5G Internet of Things (IoT) use cases with billions of connected devices and sensors.

media access control (MAC): Sublayer of the data link layer of the open system interconnections (OSI) model that controls access to the physical transmission medium in local networks.

millimeter wave (mmWave): The band of spectrum between 30 gigahertz (GHz) and 300 GHz where the wavelength is on the order of millimeters. Located between the microwave and infrared spectrums, mmWave is used for high-speed wireless communications.

multi-access edge computing (MEC): A network architecture where more processing, especially for latency-sensitive applications, stays closer to the edge of the mobile network. Formerly called *mobile edge computing*.

multi-user multiple-input/multiple-output (MU-MIMO): An application of MIMO technologies where the base station communicates with two or more devices simultaneously.

multiple-input/multiple-output (MIMO): An antenna diversity technique using multiple antennas and transmit/receive chains on both the transmit side and receive side to take advantage of multipath propagation and improve the quality and reliability of wireless communication.

network functions virtualization infrastructure (NFVI): A key component of the network functions virtualization (NFV) architecture that describes the hardware and software components on which virtual networks are built.

network management system (NMS): Enables the monitoring and management of a network.

next-generation node B (gNodeB or gNB): 5G wireless base station that transmits and receives communications between the user equipment (UE) and the mobile network.

non-standalone (NSA): A 5G network deployment that uses existing 4G Long Term Evolution (LTE) radio and evolved packet core (EPC) network control planes, but also allows carriers to begin early trials using 5G user equipment (UE) and the 5G data (or user) plane.

open radio access network (O-RAN): New radio access network (RAN) infrastructure that breaks down the traditional hardware-centric RAN into building blocks that can come from multiple vendors and are connected with open and standardized interfaces.

open radio access network central unit (O-CU): O-RAN network element responsible for the packet data convergence protocol (PDCP) layer.

orthogonal frequency-division multiplexing (OFDM): A frequency-division multiplexing scheme encoding digital data on multiple frequency channels to increase bandwidth and decrease response time. OFDM techniques allow for densely packed subcarriers without the need for guard bands and filters, increasing spectral efficiency and simplifying electronic design. OFDM is especially good in severe channel conditions where narrowband interference exists.

packet data convergence protocol (PDCP): Layer in the radio protocol stack between the radio resource control (RRC) and radio link control (RLC) layers.

physical (PHY): Layer 1 of the 5G protocol stack.

physical downlink control channel (PDCCH): The main data bearing channel allocated to users on a dynamic and opportunistic basis.

quadrature amplitude modulation (QAM): A modulation scheme that allows for more than one bit per symbol by using a simultaneous combination of both phase and amplitude modulation.

quality of experience (QoE): A measure of user satisfaction with a service.

radio access network (RAN): The part of the telecommunications network that connects user equipment (UE) to the core network and other parts of a mobile network via a radio connection.

radio access technology (RAT): The underlying physical connection method for a radio-based communication network.

radio frequency (RF): The oscillation rate of an alternating electric current or voltage of a magnetic, electric, or electromagnetic field or

mechanical system in the frequency range from around 20 kilohertz (kHz) to around 300 gigahertz (GHz).

radio link control (RLC) layer: Layer 2 of the 5G protocol stack.

radio resource control (RRC): A layer 3 protocol used on the air interface between user equipment (UE) and the base station.

radio resource management (RRM): The management of radio resources and transmission characteristics such as modulation scheme, transmit power, beamforming, user allocation, data rates, handover criteria, and error coding scheme.

RAN intelligent controller (RIC): O-RAN element that gathers information from other network elements, performs analytics, generates suggestions to optimize the RAN, and pushes the commands out to the network elements.

random access channel (RACH): The first message sent from the user equipment (UE) to the base station when the UE is powered on.

remote interference management (RIM): Reference signal that helps overcome ducting, an effect caused by changes in the refractive index of the atmosphere. RIM helps the network better understand the environment and mitigate issues.

remote radio head (RRH): The component of a base station responsible for converting the digital signal into an analog signal for transmission. Usually located on the tower in proximity to the antenna(s) to minimize signal loss.

session management function (SMF): Service-based architecture (SBA) element responsible for interacting with the decoupled data plane, creating, updating, and removing protocol data unit (PDU) sessions, and managing the session context with the user plane function.

slot form indicator (SFI): Indicates how each of the orthogonal frequency division multiplexing (OFDM) symbols within a given slot is used. The SFI denotes whether a given OFDM symbol in a slot is used for the uplink (UL), or downlink (DL), or if it's flexible.

standalone (SA): A 5G network deployment configuration where the next-generation Node B (gNB) doesn't need any 4G assistance for connectivity to the core network; the 5G user equipment (UE) connects to the 5G next generation core network (NGC or NGCN).

time-division duplexing (TDD): Duplex communication where the uplink (UL) is separated from the downlink (DL) by different time slots in the same frequency band.

ultra-reliable and low-latency communications (URLLC): One of three key use cases defined in 5G New Radio (NR), URLLC focuses on applications that require fail-safe, real-time communications. Examples include the industrial Internet, smart grids, infrastructure protection, intelligent transportation systems, and autonomous vehicles.

uplink (UL): The path of transmission from the user equipment (UE) to the base station. In 5G, the UL waveform is cyclic prefix orthogonal frequency-division multiplexing (CP-OFDM), or discrete Fourier transform spread orthogonal frequency-division multiplexing (DFT-s-OFDM).

user equipment (UE): A subscriber's mobile device, such as a cell phone, tablet, or modem.

user plane function (UPF): Network function of the 5G core network responsible for packet routing and forwarding, packet inspection, quality of service (QoS) handling, and external protocol data unit (PDU) session for interconnecting the data network in the 5G architecture.

virtualized network function (VNF): Consists of one or more virtual machines or containers running different software and processes on standard ("white box") high-volume servers, switches, and storage devices, or cloud computing infrastructure, instead of running on custom hardware appliances for each network function.

virtualized radio access network (xRAN): A type of software-based, extensible radio access network.

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